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STRATEGIC-BASED MULTI-CRITERIA DECISION MAKING

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Abstract
Decision making for critical infrastructure investments often means there will be a new allocation or distribution of scarce resources. Unfortunately the decisions made do not always reflect the needs of the system as a whole; instead they are often driven by political influence and bias. In evaluating the needs of the system as a whole, a generalized, transportable methodology for goal-oriented multi-criteria decision making is formulated. This approach may be useful for current-versus-desired critical infrastructure assessments, preliminary decision making data collection, and stakeholder analysis.

Keywords
multi-criteria decision making, strategic planning, critical infrastructure, pairwise ranking of alternatives, decision support system, conjoint analysis, stakeholder analysis, stated preference analysis

Introduction
Critical infrastructures (CI) are progressively evolving and increasingly relied upon by societies (National Research Council, 2009). Many regional systems of systems (SoS) are unsustainable as their infrastructures are vulnerable to threats, susceptible to operating inefficiencies, or operating beyond capacity (Gheorghe, Masera, Weijnen, and De Vries, 2006). Additionally, their governing policy and regulatory frameworks do not keep pace with their rapid development, expansion, and evolution (National Research Council, 2009). Before soliciting options for improvement, decisions must be made to i) identify and prioritize weaknesses in the system, and ii) assess the potential improvements that can be achieved. Despite this fact, there is an apparent lack of decision making support for identifying characteristics and metrics that evaluate the gap between the current and desired systems. At a high level, this is concerning for industrial regions which rely on complex, interconnected physical networks that can be regulated to some degree.

Many CI assessment models, approaches, and techniques exist for prioritization of infrastructure (Giannopoulos, Filippini, and Schimmer, 2012; HRPDC, 2011; Katina and Hester, 2013). Identifying underperforming processes and assets, and assessing their criticality, are daunting tasks, but necessary to optimize return on investments made to improve the system(s). Therein lies the problem in choosing a solution or strategy for alleviating system deficiencies. Depending on the system and its needs, many individual options may be available to repair, upgrade, or replace components of a system, integrate new technology, or implement changes in existing policy and procedures. Selection of a combination of solutions could also be a viable option for achieving an improved system state. There are several models and methodologies for evaluating system improvements for the CI in question and, although inherently incomplete or limited in nature, they all make reasonable attempts to weigh the possibilities of resulting benefits and achievement of system goals. Some methods and techniques use available criteria to analyze vulnerability reduction, cost effectiveness, cost utility, or maximal geographical distribution to aid the decision making process.

Insight gained through comparison assessment is prerequisite for two major concerns: 1) prioritizing CI for the allocation of scarce resources; and 2) assessing the benefits of possible resource allocations to CI. Although the current trend is to first prioritize infrastructures so that they may be allocated resources accordingly, research by Katina and Hester (2013) showed that this strategy is not transportable across sectors and regions. In synthesizing a comprehensive, generalized approach for evaluating the gap between current and desired systems, the problem statement can be answered. Consideration of influencing biases will be made to define qualitative criteria of current and desired systems in an objective manner that may also influence potential system solutions. This paper will focus on decision support for improving mission-oriented infrastructures. Ideally, this approach will be holistic and transportable across sectors and regions.

Literature Review

The literature reviewed will analyze some of the aspects of methodology in evaluating CI systems and projects, stakeholder analysis, regulation and policy governing decision making.

Critical Infrastructure Assessments

Katina and Hester (2013) performed a holistic study on a plethora of criticality factors cited with regards to their relevance to various regions and industrial sectors. The following four general categories of criticality factors were then identified for use in prioritizing CI:

1. *Resiliency:* an infrastructure's ability to bounce back after failure, measured by defensive properties;
2. *Interdependency:* the degree of interconnectedness within the system;
3. *Dependency:* the degree that users rely on an infrastructure; and
4. *Risk:* the likelihood that a system will be affected by negative impacts.

These four categories are an important starting point for addressing the first part of CI assessment: defining the current system state through criticality assessment. Next, we will look at some methodologies that may provide insight for addressing the gap between current and desired system states.

Facility criticality and agility. The International Space Coast Transportation Planning Organization (SCTPO) designed an infrastructure analysis methodology that assesses facility criticality (the level of influential operational efficiency) and agility (the ability to adapt to changing future conditions) (Kamm, 2011). The methodology addresses some important considerations within the first three criticality factors by Katina and Hester (2013).
The first assessment, facility criticality, analyzes the following elements (Kamm, 2011):

1. Regional importance to economy, national defense, security, safety and/or overall mobility;
2. Level of multimodal activity, actual impact on goods movement within the area;
3. Location and accessibility to regional goods movement corridors;
4. Secondary functions, type and level of secondary facility activities, degree of diversification;
5. Operational impacts if functions disrupted or suspended;
6. Other critical facilities served, supported or depended upon; and
7. Placement within complementary network, functional connectivity with other assets.

This analysis can help predict an infrastructure's contribution to the overall operational efficiency (criticality) of a regional SoS through consideration of its relevance to society and essential interdependent exchanges.
The goal of studying agility criteria is to assess the ability of the infrastructure's surrounding area to hinder or assist multimodal facilities in quickly responding to new or novel future conditions (Kamm, 2011). They include:

1. Location
2. Condition (safety, reliability, vulnerability, sustainability)
3. Disaster and disruption mitigation and response
4. Maintenance and improvement responsibility
5. Security
6. Accessibility
7. Significance
8. Modal connectivity
9. Modal use conflict and mitigation
10. Future demand

These criteria can then be considered to predict the facility's agility.

Comprehensive risk. Pendit, et al. describes risk as a function of three elements: the *threats* to which an asset is susceptible, the *vulnerabilities* of the asset to the threat, and the *consequences* potentially generated by the degradation of the asset. The DHS defines risk as "*the potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences*" (Pendit, et al., 2013). A critical structure's vulnerability can also be focused on three elements (Zio and Milano, 2009): (i) the degree of loss and damages that would be result due to impact of a hazard; (ii) the degree of exposure, or likelihood of being exposed to the hazard; and (iii) degree of capacity of resilience (the ability of a system to anticipate, cope with or absorb, and recover from the hazard's impact.
Baker (2005) described a comprehensive vulnerability assessment methodology for individual CI facilities that accounts for both physical and cyber threats against a facility's mission-critical systems. The following objectives of the methodology were defined (Baker, 2005):

- Understand the facility/organization's mission and mission-supporting system functions.

- Identify mission-threatening vulnerabilities of critical facility systems.
- Understand system design and operation in order to determine failure modes and likelihoods.
- If possible, identify direct consequences of system failures as well as any cascading effects.
- Recommend facility improvements to reduce vulnerability.

The results of the methodology are intended to offer a strategy for making resilience-improving investments by following this process (Baker, 2005):

1. Identify infrastructure's threats and hazards.
2. Identify the infrastructure's mission(s) and primary function(s) to complete these missions.
3. Identify sub-system(s) that perform facility missions.
4. Trace and define relationships among critical systems.
5. Model facility operations including mission and support system vulnerabilities, interdependencies, and reconstitution times when subject to threats of concern.
6. Determine which systems will be affected by threats that are mission-critical. Trace cascading failures to determine if other systems will fail as a result of the initial system's failure.
7. Define the system's upstream and downstream dependencies (external to the facility). Estimate their downtime durations and operational effects on the mission-critical functions of the system in question.
8. Review mission-critical personnel and their responsibilities and demand/availability in the event of a major threat or disaster.
9. Develop or review existing contingency plans that prescribe procedures, protocol, and responsible individuals in the event of system failures. Identify redundancies, backup systems, and time necessary to deploy.
10. Consider planned system changes, upgrades, moves, and acquisitions.

This assessment takes the International Space Coast Transportation Planning Organization's methodology further by analyzing an individual facility's resilience and vulnerability against specific threats and hazards.

Objective Acquisition for Addressing the Gap

Spurlin (2007) described a four-step assessment process for determining the gap between current and desired states of technology infrastructure in educational institutions, with the goal being that implementation of the framework would facilitate rapid decision making for technology acquisitions and upgrades. The methodology was designed to assess a particular industry's technology infrastructure (hardware, software, networks, and facilities; also, technology-enabling people, processes, and policies), although they can easily be generalized for transportability.

1. Identify the desirable learning goals and outcomes of the system through benchmarking or needs assessment committees.
2. Utilize available resources to identify instructional methods or "pedagogies" (in effect, *processes*) that will best increase the desired outcomes in Step 1.
3. Determine which technologies would best facilitate Step 2 (as well as which technologies *currently* best support them) by conducting interviews, surveys, or focus groups.
4. Evaluate the available technology resources and infrastructure compared to those defined in Step 3.

Various tools and techniques may be used for any of the above steps, including direct observations, questionnaires and surveys, expert judgment, focus groups, literature reviews, formal reports, performance assessments, and user reflection (Spurlin, 2007). Gap evaluation can then be used to assess the feasibility of investments defined in step 4 that meet the defined objectives of the system.

Stakeholder Involvement

Spurlin's needs assessment methodology prescribes the traditional recommendation to include those with power, influence, and legitimacy in the decision making process in order to define a holistic picture of the gap between existing and desired infrastructure (Spurlin, 2007). To successfully provide decision support for the evaluation of a system's gap, cooperation must come from both facility management as well as facility workforce to provide consistent worldviews regarding industry challenges and safety culture (Johnsen, Vatn, Rosness, and Herrera, 2006; Berg, 2009;). Key elements of safety culture include reporting culture, shared commitment and level of care for hazards, systemic evaluation of rules and regulation, industry wide cooperation and information sharing, and legislative cooperation (Johnsen, et al., 2006). The inclusion of industry and regional experts is key for meaningful analysis. Berg (2009) makes the point: "Information is another element of basic industry conditions: to what extent did perceived information asymmetries stimulate interest in the creation of new institutional arrangements, creating an agency with the expertise needed to provide oversight for the sector?" (p. 3).

Interestingly enough, many infrastructure investments and resource allocations are decided at the highest levels of government (within the executive branch), while independent agencies develop and enforce service, economic, and safety regulations for each mode, yet are absent from budget negotiations (Dunn and Sussman, 2011).

Auserwald (2005) emphasized the fact that public support is difficult to achieve due to perceived high costs and consumer inconvenience. Any proposed change to the current system state (as well as perceived effects) may prove to be controversial with the public and sabotaged in the media. Therefore, community representation would also be beneficial for discussions on the gap between the current system state versus the desired future system state. Aside from the fact that involving the public is “acting in accord with basic democratic principles,” and “more than simply following legislation and regulations” (Bailey & Grossardt, 2010).

Achieving Desired Critical Infrastructure

A potential future system state can be evaluated after changes have been made to the current system state by means of investment in products, people, processes, or policy reform. This is generally a very complex endeavor utilizing fuzzy and subjective logic, and vastly prone to human error, hence the need for decision support systems to identify significant deficiencies to which scarce resources would be allocated.

Investment in assets. Cost-benefit analysis is most often used for prioritizing CI investments. The cost-effective selection processes measure the implementation of the risk-reduction method against the benefit derived by the reduced risk, enhanced reliability, and improved efficiency. Reaching a breaking point of marginal cost versus marginal benefit is an option, as is investing in maximum benefits given a fixed budget (Moteff, 2005). This can be a dangerous practice; Flyvbjerg (2009) explains, as “perverse incentives encourage promoters to underestimate costs and overestimate benefits” (p. 334). Large organizations have trouble prioritizing projects because there is always more demand than available resources, and political power influences the manner in which they are prioritized (Sowlati, Paradi, and Suld, 2005). This further drives the point that a more democratic process is needed to avoid embarrassing investments in major infrastructure assets.

Risk reduction that benefits a larger number of assets may prove to most effectively reduce system vulnerability. Maximizing the number or geographical distribution of assets for which risks are reduced may also be used. Another possibility is that efforts are directed at reducing threat scenarios or protecting potential targets (Moteff, 2005). As a general rule, protection costs are not to exceed a reasonable percentage of the total asset value, and acceptable amounts of risk should be achievable at acceptable costs (Roper, 1999).

Investment in reform. Most CI assessment and evaluation methodologies fail to incorporate social and organizational aspects into the analysis, although arguably the most important (Solano, 2010). An investigative report of a failed offshore oil and gas drilling and production platform in the North Sea, by Bea et al. (2009), concluded that 80% or more of the causes of failure were firmly rooted in human, organizational, and institutional malfunctions, while the rest were attributed to physical component malfunction.

Current infrastructure markets operate under antiquated regulatory systems that have not kept pace with the evolution of new infrastructure technologies and increasing interdependencies. The absence of clear fiscal responsibility for funding CI upgrades means that most projects are unlikely to be completed. These markets are also unappealing from an investor viewpoint, due to the lack of financial incentive and uncertainty involved with measuring project success.

It is essential for policy development decisions to account for tradeoffs between firms’ efficiency and vulnerability, and the governing systems and incentives affecting those firms. According to Auserwald (2005), regulation must:

- Structure incentive systems for investments that enhance prevention of, response to, and recovery from the most likely and damaging attacks;
- Ensure robust internal operations and greater system reliability of private firms; and
- Guarantee competitiveness by limiting imposed costs on firms.

Brown, et al. (2005) suggested that substantial vulnerability reduction is achievable through planning, and only modest investments in new physical infrastructure. Relocation of structures and loads can also provide enormous benefit without high costs associated with adding redundancy capacity or hardening components.

Water and wastewater services are mainly provided by public agencies, though transportation infrastructures are owned by both public and private organizations, thus the need for combined consensus. It is important to note: CI investments are meant to improve sustainability, reliability, and safety (i.e. necessary expenditures). Over the next decade, significant investments will be made by the private sector as well as all levels of government to upgrade U.S. infrastructure, under increasingly volatile circumstances and with a drastic shortage of necessary resources.

Difficulty in Decision Making

Depending on the stakeholders' backgrounds, vantage points, and interests, different perceptions and attitudes can be adopted in response to the same information. For this reason, it can be emphasized that decision making analysis must be as non-objective and unbiased as possible (Aven and Krohn, 2013).

Some criteria used for weighing alternatives cannot be condensed into monetary value, which complicates making comparisons and trade-offs since a common unit does not exist. However, even with the use of a common unit, stakeholder preferences and needs are lost in translation (Linkov and Ramadan, 2004).

Metrics used to quantify aspects of current and potential system states are often not transparent enough to estimate the returns of CI investments. This uncertainty makes it difficult to obtain public support, and to make unbiased, objective decisions to improve regulation and fund research and development projects (National Research Council, 2009). Unfortunately, many systems are neglected until they fail or are on the verge of failing completely. Maintenance and repairs are also often delayed without legislative earmarks or scandalous media attention. The National Research Council (2009) identified a need for new approaches to decision making related to CI.

Methodologies in this literature review showed that evaluating critical infrastructure often takes the overall mission or goal into consideration during vulnerability, resilience, and gap assessment methodologies, though this is not a typical focus found in CI project selection decision making literature (Baker, 2005; Spurlin, 2007). One multi-criteria decision making study was found using strategic planning as a focus, where the potential direct, symbiotic, and network-based futures were considered, as they resulted from alternate business strategies (Montibellar and Franco, 2010).

It becomes apparent that any investment should have some alignment with intended goals, and a major consideration when allocating scarce resources. These assessments are overwhelming for policy makers, thus a need for support in this area. Decision support in this area may provide a good foundation for preliminary system analysis and stakeholder analysis, both, which are contextually relevant for scarce resource allocation. For this reason, the traditional project selection process is unnecessary, as the desired methodology will first evaluate the most appropriate areas for investment *before* soliciting project proposals.

Problem Statement

Assume a region or sector is developing a strategic plan for investment, and has identified some potential areas (alternatives) to which resources may be allocated. Definitive sub-goals (criteria) that characterize the desired future state have also been identified, and consensually agreed upon by all relevant stakeholders involved in the decision making process. Each alternative can then be assigned a score for each criterion, based on their individual degree of sub-goal orientation. How might the alternatives be scored?

This paper will consider a nonconcrete example involving a hypothetical country wishing to make preliminary decisions about how to allocate scarce resources to four potential infrastructure sectors. Information has been provided on how likely the country's strategic plan will be positively impacted through investments made to achieve each particular aspect of the desired state.

Assume that the country is considering investments in their water, energy, transportation, and communication sectors, to improve their current state through improvements in the following: economic competitiveness, quality of life, sustainable development, environmental health, and social inclusion (see Exhibit 1 for possible interpretations and metrics for each).

Exhibit 1. Possible Sub-goals of a Strategic Plan.

Categorical Benefit	Possible Considerations for Rating/ Measuring Investment Alternatives
Economic	• Support relative growth/stability of GDP • Increases economic competitiveness
Quality of life	• Gross National Happiness (GNH) • Life expectancy and overall health • Standard of living
Sustainable development	• Ability to meet increasing demand with limited socio-economic impact over time • Prevent impending crises (forecasted risk

	and reliability data)
Environmental health	• Accessibility of sustainable resource per capita • Limited ecological impact over time (emissions, changes in wildlife, etc.)
Social inclusion	• Supports public interest, social rights and civil liberties • Increased access to social services and labor markets

Likert's ratings from 1 to 5 were assigned to each of the four alternative investment areas (a total of 20 data points) for their perceived alignment with the five different criterion sub-goals. Depending on the measurements and metrics chosen for the decision maker(s), presumed to be suitable for measuring sub-goal achievement within the strategic plan, the following Likert's scale can be used to assign impact ratings for each possible area of investment (Exhibit 2).

Exhibit 2. Likert's Scale for Rating Alternative Investments in Each Sub-goal Category

Rating	Interpretation
1	Investments will not impact goal
2	Investments will not likely impact goal
3	Investments will somewhat impact goal
4	Investments will moderately impact goal
5	Investments will significantly impact goal

Ultimately, this data collection and preparation for the decision support software use (to be discussed in the next section) is culturally subjective to the decision maker(s), and may be influenced by the availability of particular data sets, forecasts, accuracy of the research, available resources, and the manner in which metrics are normalized. It is to be expected that any methodology will require some consideration and accommodations to be made in order to conform to case-by-case circumstances.

Solution Methodology

1000Minds Ltd. provides web-based DSS for multi-criteria decision making (MCDM) that can be used for considering alternatives and the allocation of scarce resources (Baizyldayeva, et al., 2013). The DSS applies the PAPRIKA (Potentially All Pairwise RanKings of All Possible Alternatives) method of conjoint analysis, also called stated preference analysis.

1000Minds software collects data on each alternative's individual criteria, allowing the user to assign separate rating scales (from low to high) for each criterion. The decision maker then makes tradeoffs between pairwise attributes of two alternatives at a time, typically in a sequence of 50 to 100 hypothetical scenarios. For each scenario, the decision maker indicates a preference for either alternative A or B, electing "no preference" when the alternatives appear balanced. Exhibit 3 shows an example of a tradeoff decision that the decision maker must make. For this project, my own values were tested in 89 scenarios. Statistical significance is established by the 1000Minds DSS to reveal consistency in the stakeholder's answers. Additional decisions may be answered and previous questions may be repeated to ensure reliability in the responses provided by the decision maker.

Exhibit 3. Example of Hypothetical Scenario

Both standalone and group decision making activities can benefit from this method. It is especially helpful for prioritization and discovering stakeholder preferences (Baizyldayeva, et al., 2013).

Justification of Method

The major benefit of using conjoint analysis is the ease of producing aggregated data into combined results that are defensible and reflect alignment with true stakeholder values. Because infrastructure investments require significant commitment of scarcely available resources, obtaining stakeholder consensus is a critical part of demonstrating a legitimate need to plan the project. The tool selected provided a means for how this could be accomplished.

Although other scoring methods could have been used, PAPRIKA provided a satisficing method for the purpose of this case study by enabling pairwise comparisons of undominated pairs, which compare the preference of two criteria per judgment to eventually lead to the decision-makers' true preferences. In a real-world application, it is expected that multiple decision-support systems would be used for comparison.

Results

Ratings were assigned to each alternative's forecasted impact using hypothetical data. As discussed in the previous section, the discretion of the decision maker would influence actual ratings in a real application.

Based on the inputted data, and the expressed preferences revealed through responses to 89 hypothetical scenarios, the 1000Minds software results calculated weights (preference values) that express the overall relative importance of the defined criteria and assigned ranks to each alternative (Exhibit 4).

Exhibit 4. Ranked Alternatives.

Alternative	Economic Benefit	Quality of Life	Environmental Health	Sustainable Development	Social Inclusiveness	Rank	Total score
Invest in Water Infrastructure	3	5	5	4	2	1st	71.6%
Invest in Energy Sector	5	3	4	5	3	2nd	68.6%
Invest in Transportation	5	2	3	3	4	3rd	56.7%
Invest in Communications	3	1	1	3	5	4th	39.4%
Preference Values	22.8	32.9	8.1	12.3	23.9	avg	59.1%

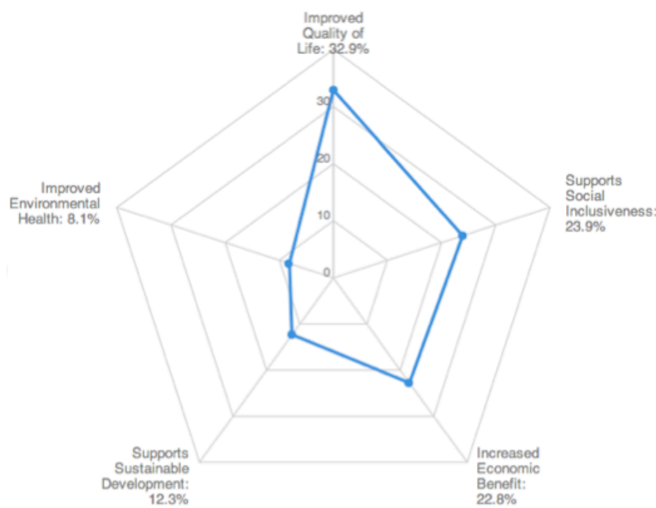
Exhibit 5 reveals the relative importance of expressed values. Based on the responses to each of the questions, a strong preference for infrastructures that improve quality of life was revealed. It is assumed then that hypothetical stakeholder (whose responses proved to be statistically reliable, as tested in 1000Minds) perceived the current quality of life in his or her region to be drastically different than that outlined in the strategic plan, and thus highly values investments that will significantly impact the attainment of that goal.

Exhibit 5. Established Weights by Relative Importance.

	Improved Quality of Life	Supports Social Inclusiveness	Increased Economic Benefit	Supports Sustainable Development	Improved Environmental Health
Improved Quality of Life		1.4	1.4	2.7	4.1
Supports Social Inclusiveness	0.7		1.0	1.9	3.0
Increased Economic Benefit	0.7	1.0		1.8	2.8
Supports Sustainable Development	0.4	0.5	0.5		1.5
Improved Environmental Health	0.2	0.3	0.4	0.7	

Finally, the radar chart displays a graphical visualization of the preference values revealed in the results (Exhibit 6). In this case study, it reveals that the dominant stakeholder preference is improved quality of life.

Exhibit 6. Radar Chart.



Conclusion

The goal outlined in the proposed topic was to develop a comprehensive, generalized approach to evaluating the gap between current and desired systems, with the intention of selecting improvement projects that best align with the strategic plan rather than simply those with the best (superficial) benefit-cost ratio. Constructing a transportable model for the problem statement was a complex process in which a concrete model was difficult to formulate. Further research in this area would benefit from a narrower scope, though the goal-oriented MCDM approach did reveal promising results in demonstrating an effective gap assessment methodology. At the very least, strategic planning based MCDM provides a supplemental or preliminary assessment for evaluating areas of investment. Additionally, the concept may be further explored in stakeholder analysis and management research.

To the author's knowledge, no prior research has produced a transportable critical infrastructure gap assessment methodology. The task becomes especially complex when the desired methodology is replicable across sectors and regions, requiring a considerable amount of preparatory data collection and analysis before the implementing the decision making model.

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